



HEV's: Here and Now TOPTEC

Trading off HEV Fuel Economy and Emissions through Optimization

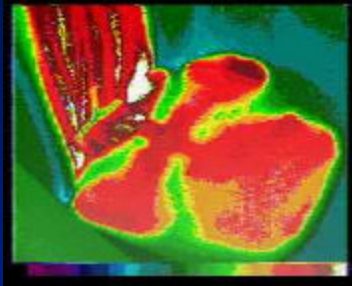
Steven D. Burch
National Renewable Energy Laboratory

May 26, 1999

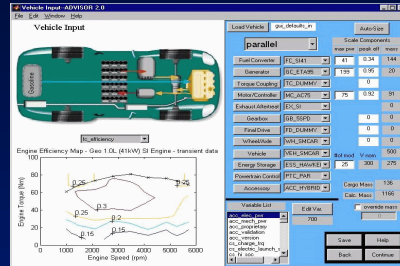
Acknowledgements

- NREL: Keith Wipke, Valerie Johnson, Tony Markel, Sam Sprik, Terry Penney
- VR&D: John Garcelon

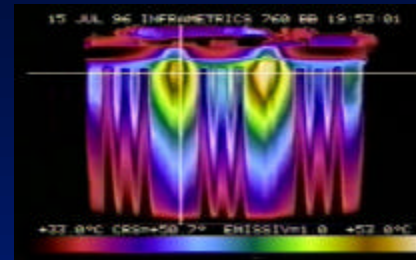
DOE Hybrid Electric Vehicle Program



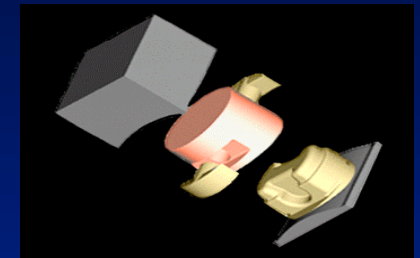
Vehicle Climate Control



Vehicle Systems Analysis



Battery Thermal Management



Vehicle Systems Virtual Prototyping

Big 3 Partnership
(55 mpg, mid-size vehicle)



Chrysler



Ford



GM

Outline

- Background
- Vehicle Design Tradeoffs
- Vehicle Control-Strategy Tradeoffs
- Effect of Drive Cycle
- Conclusions/Current Activities

Background

- Push for higher fuel economy: CAFE, global warming
- Push for lower emissions: EPA Tier 2, CARB LEV-II
- Some efforts help both: reduced mass, aero drag, rolling resistance, and auxiliary loads
- For conventional vehicles, tradeoffs include:
 - CI vs SI engine (better MPG, worse NOx & PM)
 - Engine “tuning” (timing, A/F ratio, etc.)
 - Use of EGR (better NOx, slightly worse MPG)
- HEVs provide additional optimization potential

Approach for HEV Tradeoff Study

- Select vehicle, drive cycle, and performance objectives
- Model vehicle behavior (fuel use and emissions)
- Predict the effect of different design and control options
- Perform multi-dimensional optimization on key options
- Check applicability to other vehicle and cycle types

Baseline Vehicle Configuration

- Vehicle: “PNGV-type” mid-sized 4-door ($A_f = 2 \text{ m}^2$)
 - Reduced “glider mass” (500 vs ~900 kg), aero drag (0.20 vs ~0.33), rolling resistance (0.007 vs ~0.009), & auxiliary loads (700 vs ~1000 W)
- Required vehicle performance: Gradability: 6.5%, acceleration: 0-60 mph in 12s, 40-60 mph in 5.3 s
- Fuel economy evaluated on US EPA city/hwy cycles, emissions evaluated on US EPA city cycle (FTP-75)
- Conventional, series (power follower), & parallel with:
 - Base engine: 1.9 l VW TDI
 - Advanced high-power lead-acid batteries (in series and parallel)
 - All components scaled (mass and peak power) to deliver equal performance

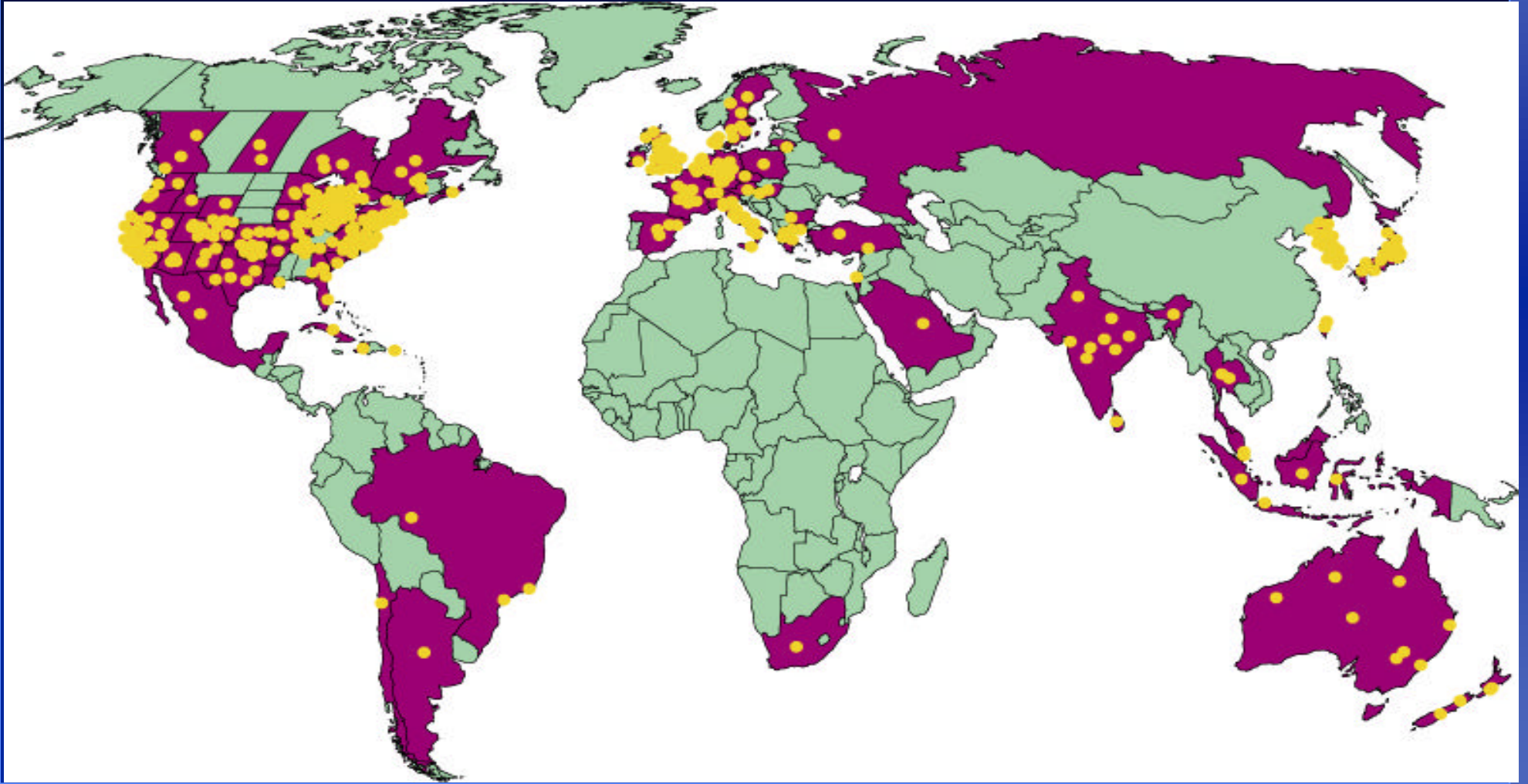
Background on ADVISOR



- ADVISOR = **AD**vanced **V**ehicle **S**imulat**OR**
 - simulates conventional, electric, or hybrid vehicles (series, parallel, or fuel cell)
- Created in '94 to support DOE HEV Program at NREL
- Freely distributed via: www.ctts.nrel.gov/analysis
 - Current version (2.1.1) released on web 4/13/99
 - Users provide component data and validation

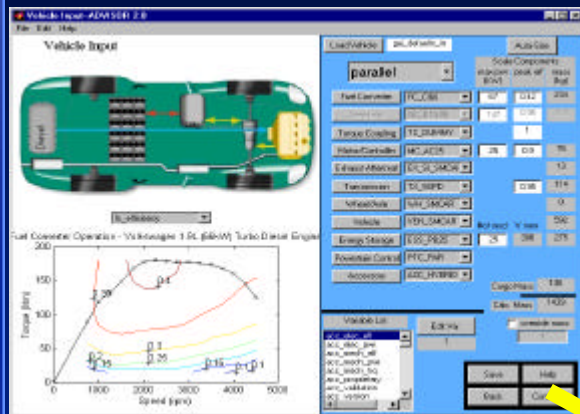
ADVISOR Being Used Globally

May 1999: ~600 users

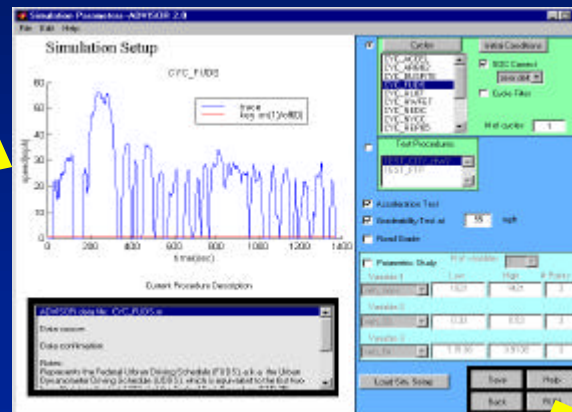


Three Main ADVISOR Screens

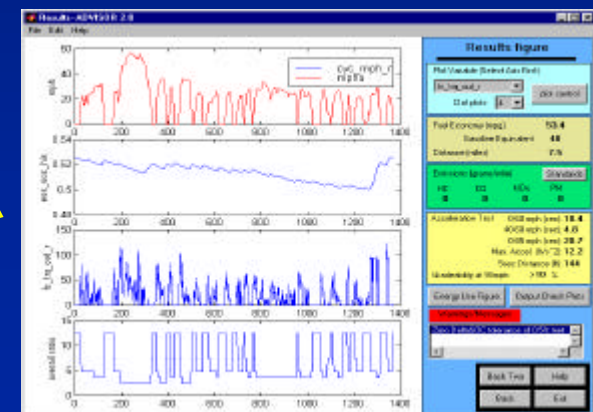
Vehicle Input



Simulation Setup



Results



ADVISOR Test Procedures Available

FTP Test

FTP Results--ADVISOR 2.0

File Edit Help

FTP Results

Fuel Economy (mpg)

mpg **42.1**

Gasoline Equivalent **37.2**

Emissions (grams/mile)

	HC	CO	NOx	PM
Bag 1 (0-505 sec)	0.673	2.078	1.752	0.203
Bag 2 (505-1374 sec)	0.165	0.248	0.811	0.056
Bag 3 (1374-end sec)	0.156	0.266	0.956	0.056
Weighted Total	0.268	0.633	1.046	0.056

Note: Total emissions is weighted as follows:
 $Total = (0.43 \cdot Bag1 + Bag2 + 0.57 \cdot Bag3) / (0.43 \cdot dist1 + dist2 + 0.57 \cdot dist3)$ where Bag* is in grams and dist* is in miles

Close

City/Hwy Results--ADVISOR 2.0

File Edit Help

Combined City/Highway Cycle

Fuel Economy (mpg)

	City	Hwy	Combined
City	43.2	42.7	
Hwy	59	58.4	
Combined	49.1	48.6	

Emissions (grams/mile)

	HC	CO	NOx	PM
City	0.252	0.887	0.231	0
Hwy			Ratio of Hwy/City NOx: 0.67	

Note: City values based on one cold-start FTP-75 cycle. Highway values based on one hot-start HWFETS cycle. Combined fuel economy $FE_{comb} = 1 / [(1/55 \cdot 1/MPG_u) + (1/45 \cdot 1/MPG_H)]$

Close and Return to Simulation Figure

J1711 Test Results--ADVISOR 2.0

File Edit Help

SAE J1711 Test Procedure Results

Final

Fuel Economy (mpg)	Emissions (grams/mile)			
	HC	CO	NOx	PM
26.7	0.345	2.101	0.605	0

Final, Cycle level

	MPG	HC	CO	NOx	PM
FUDS	23.6	0.478	4.046	0.774	0
HWFET	31.7	0.197	0.794	0.463	0
US06	28.6	0.294	0.682	0.505	0
SC03	29.9	0.325	1.335	0.737	0

Partial Charge Test

PCT-HEV
SOC info

Full Charge Test

FCT-EV,UF
FCT-EV
Add Info

FCT-HEV,UF
FCT-HEV
Add Info

SOC values for PCT-HEV

	init	pause	end	min	max
FUDS	0.504	n/a	0.549	0.535	0.573
HWFET	0.54	0.535	0.728	0.518	0.552
US06	0.54	0.574	0.626	0.561	0.587
SC03	0.54	0.464	0.527	0.454	0.474

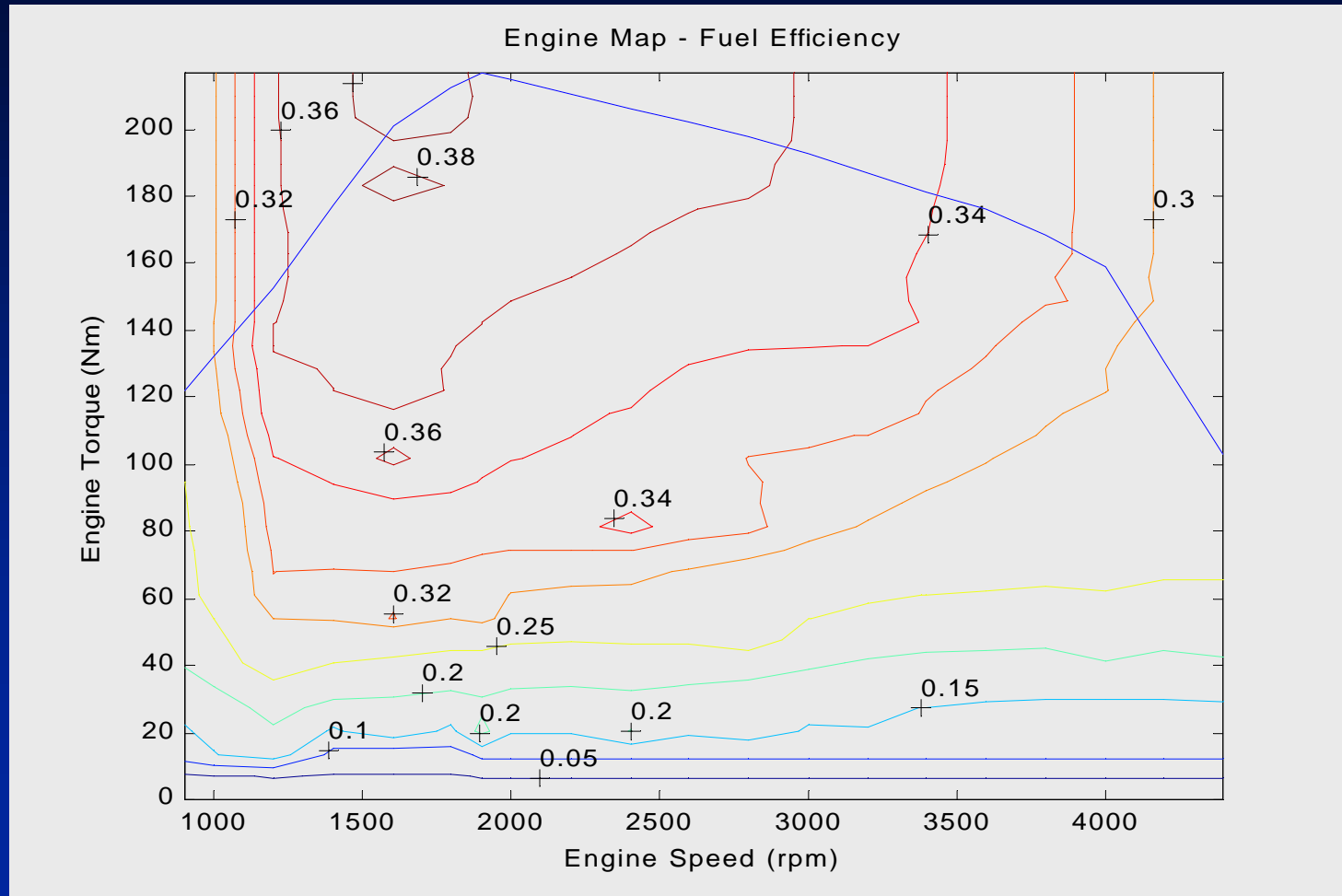
* Calculated based on +1% fuel energy

Back Two Help
Back Exit

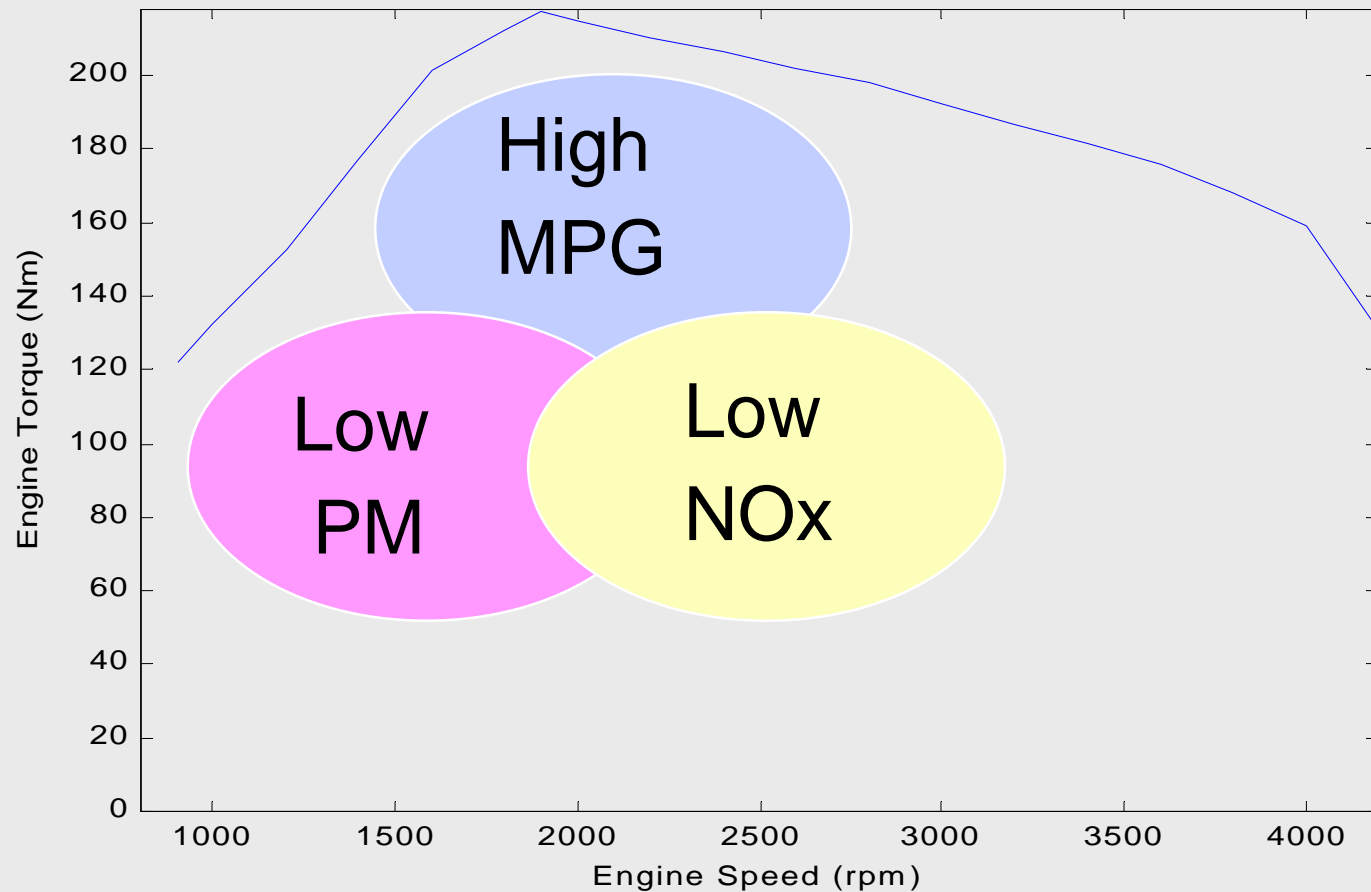
Combined City/Highway

SAE J1711 HEV Test Procedure

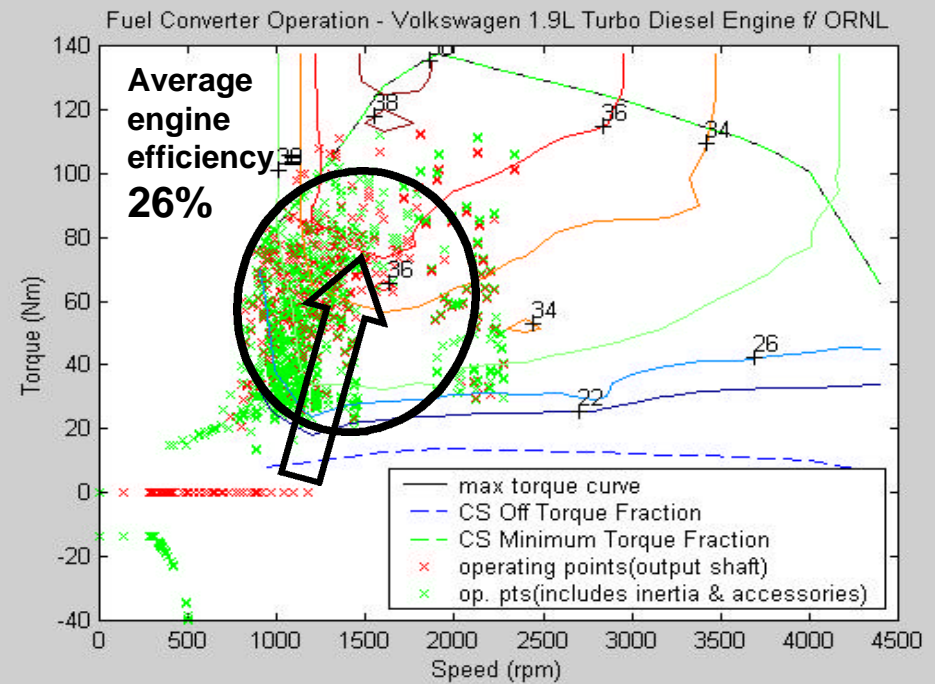
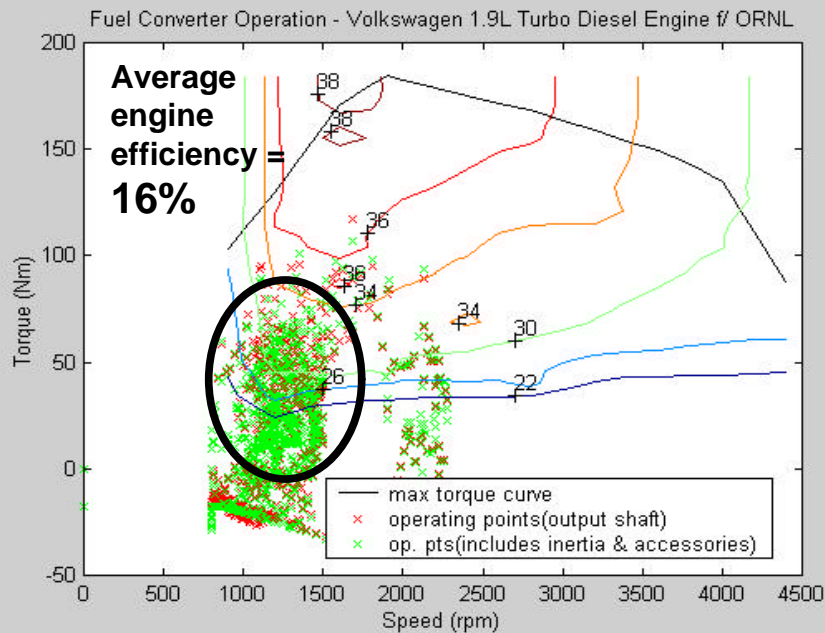
Efficiency map for CIDI engine



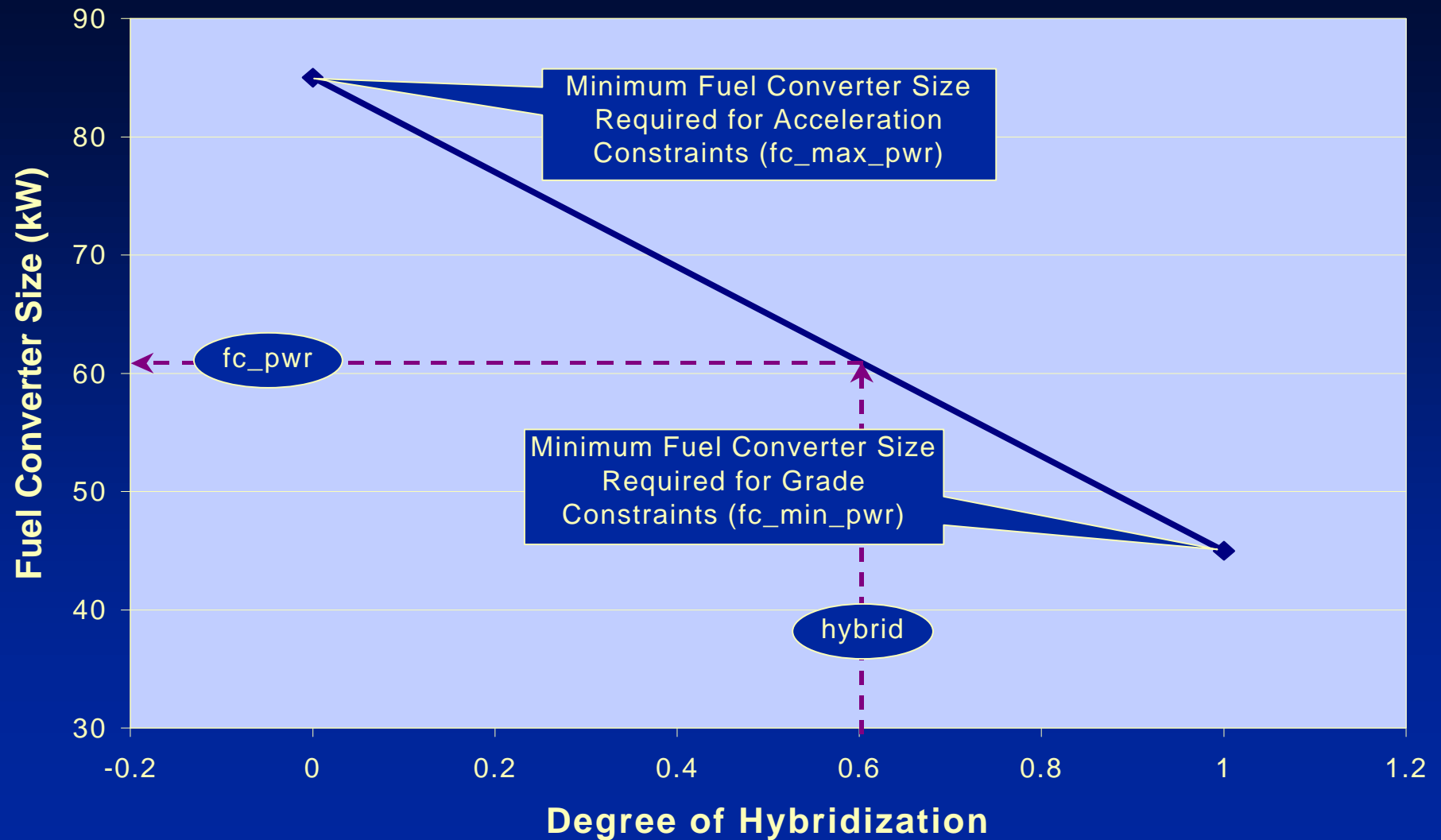
For this CIDI engine, different regions provide different benefits

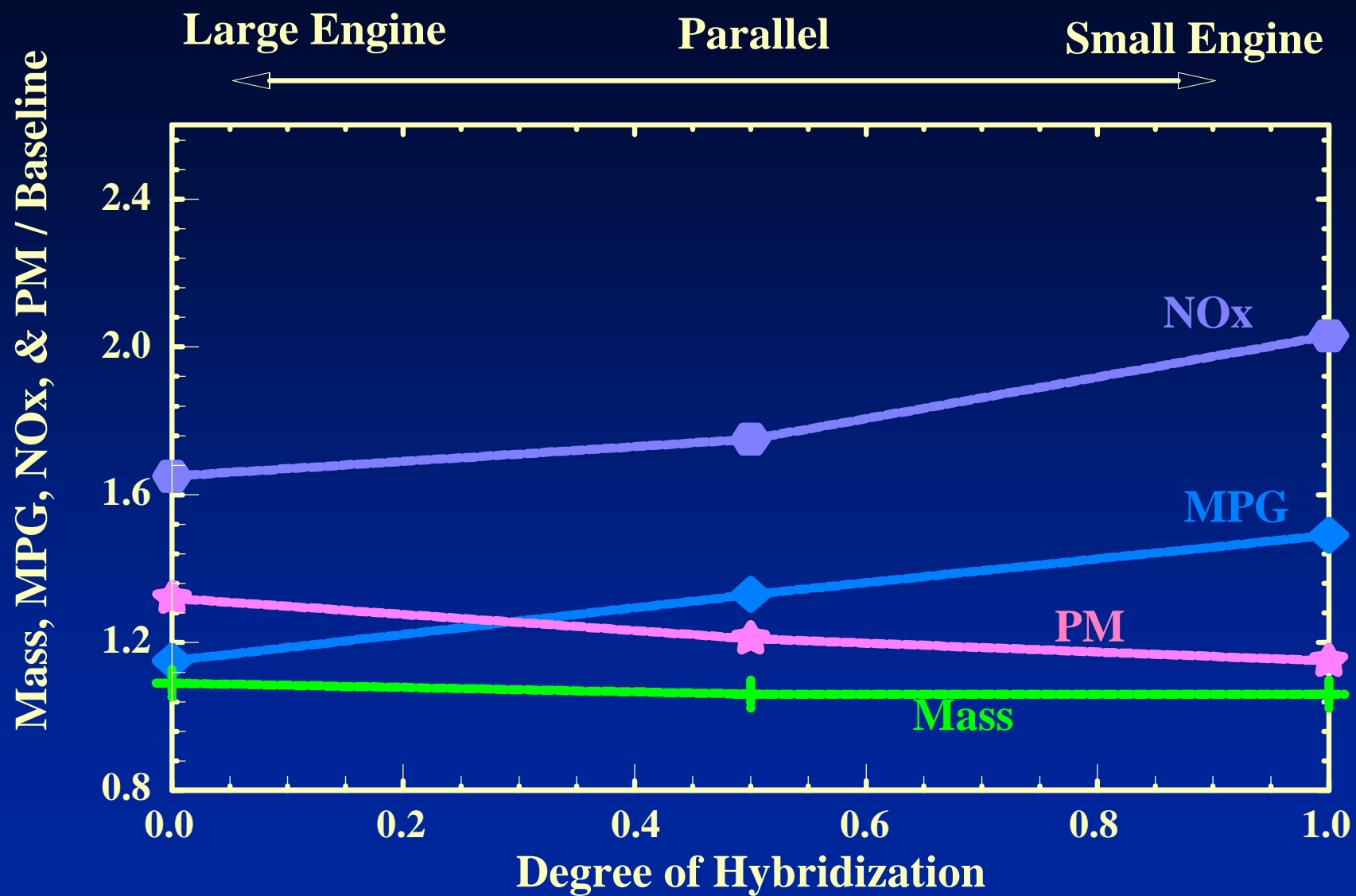


Parallel hybridization
helps move operating
points into higher
efficiency regions

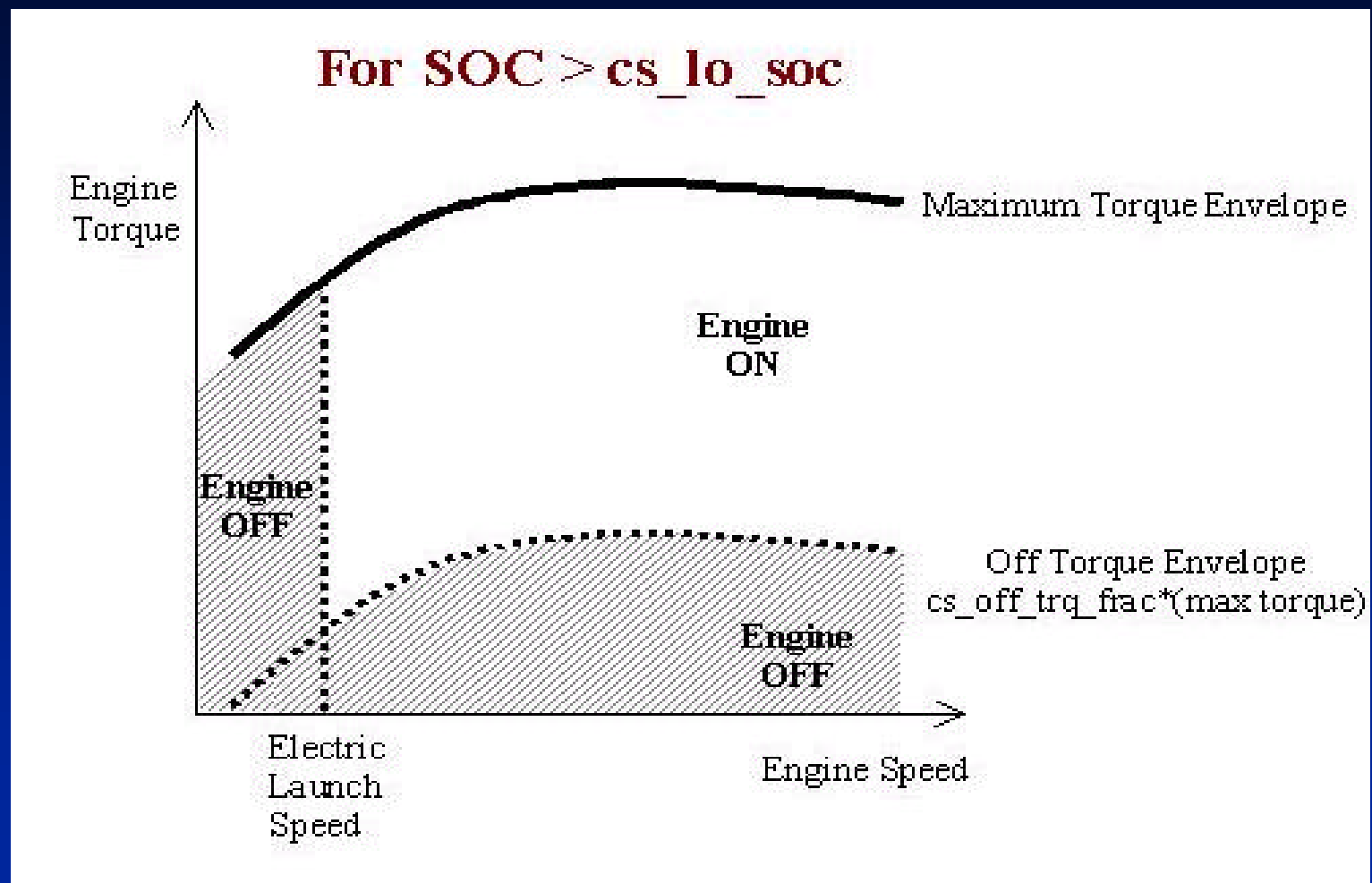


Degree of Hybridization: Definition



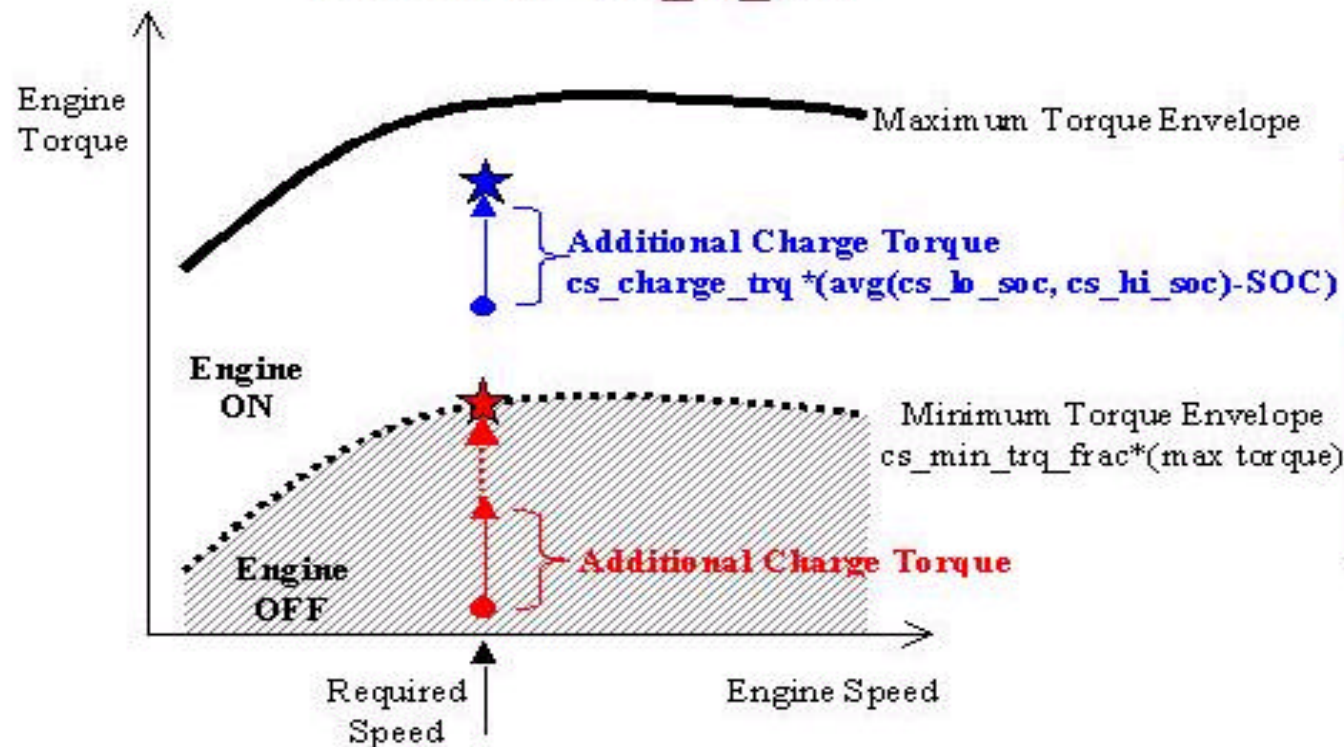


Parallel HEV Control Strategy



Parallel HEV Control Strategy

For SOC < cs_lo_soc

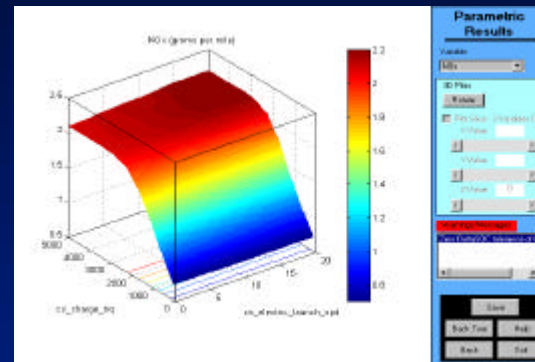
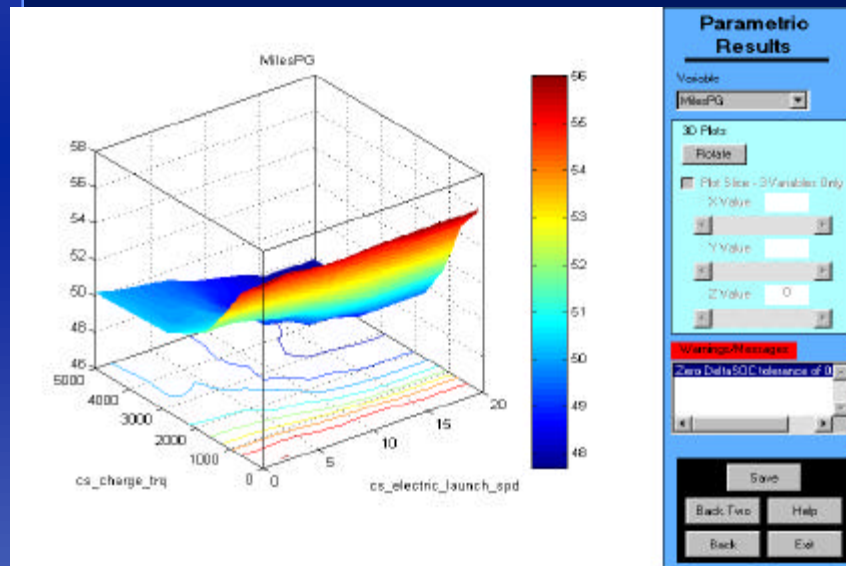


★ Case 1 (blue): Operation point is required torque plus charge torque

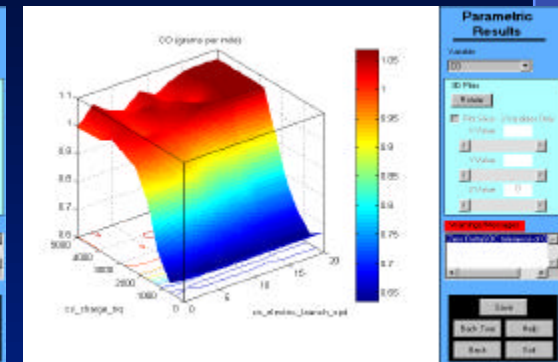
★ Case 2 (red): Operation point lies along minimum torque envelope because required torque plus charge torque is too low

Trade-Offs Between Fuel Economy and Emissions Become Visible in Parametric Studies

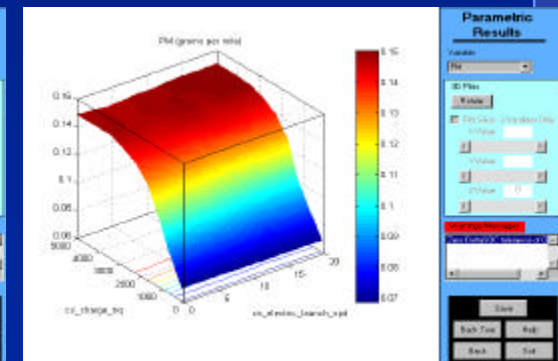
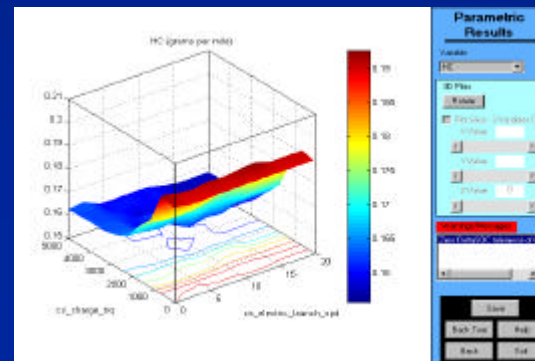
Fuel Economy



NOx
HC



CO
PM



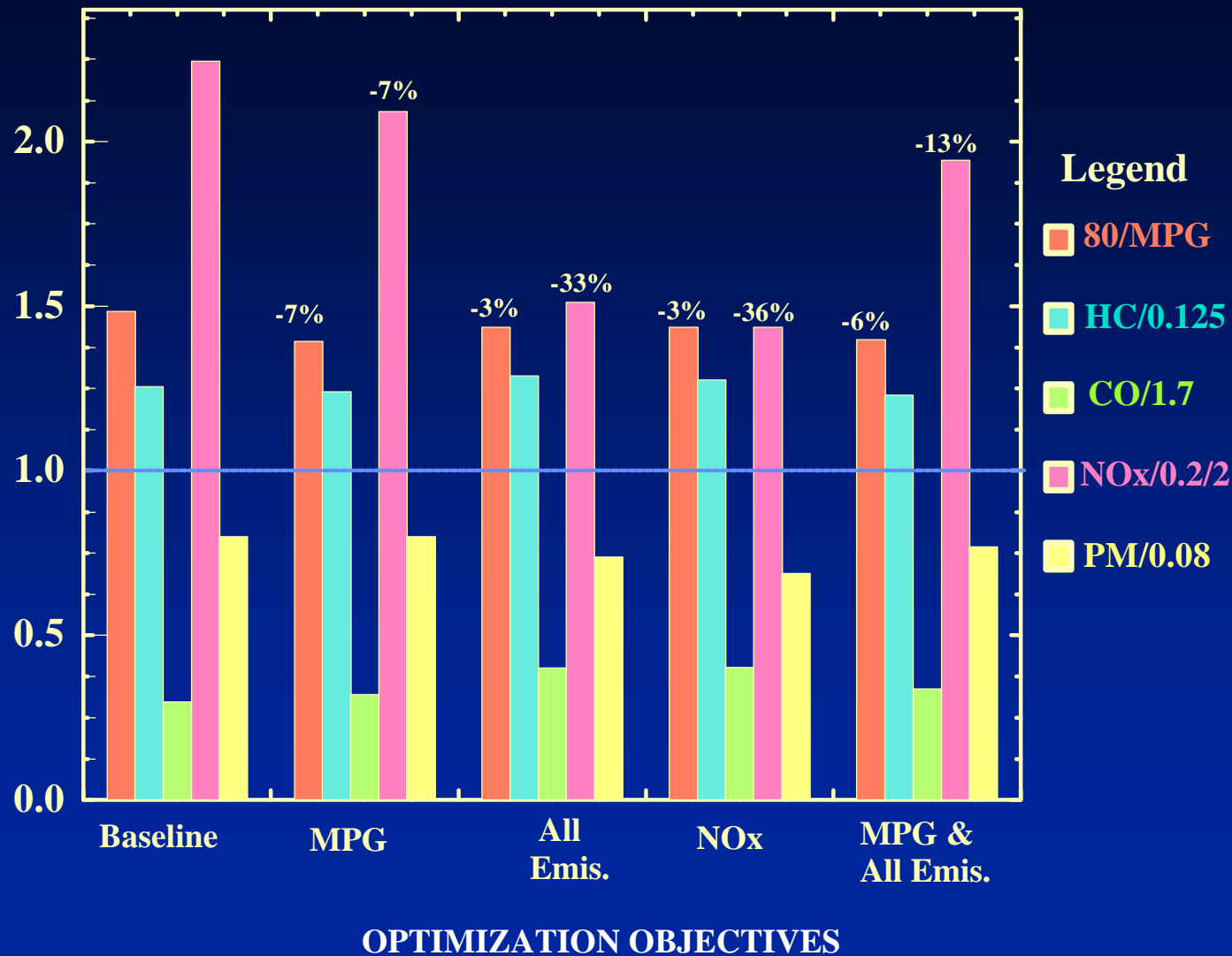
Full Optimization Allows Efficiency/Emissions Tradeoffs to be Performed Mathematically

- Goal: Balanced fuel economy and emissions
- Define an objective function that:
 - Includes emissions and fuel economy
 - Normalizes values to targets
 - Includes “tuning” parameters

For example, minimize :

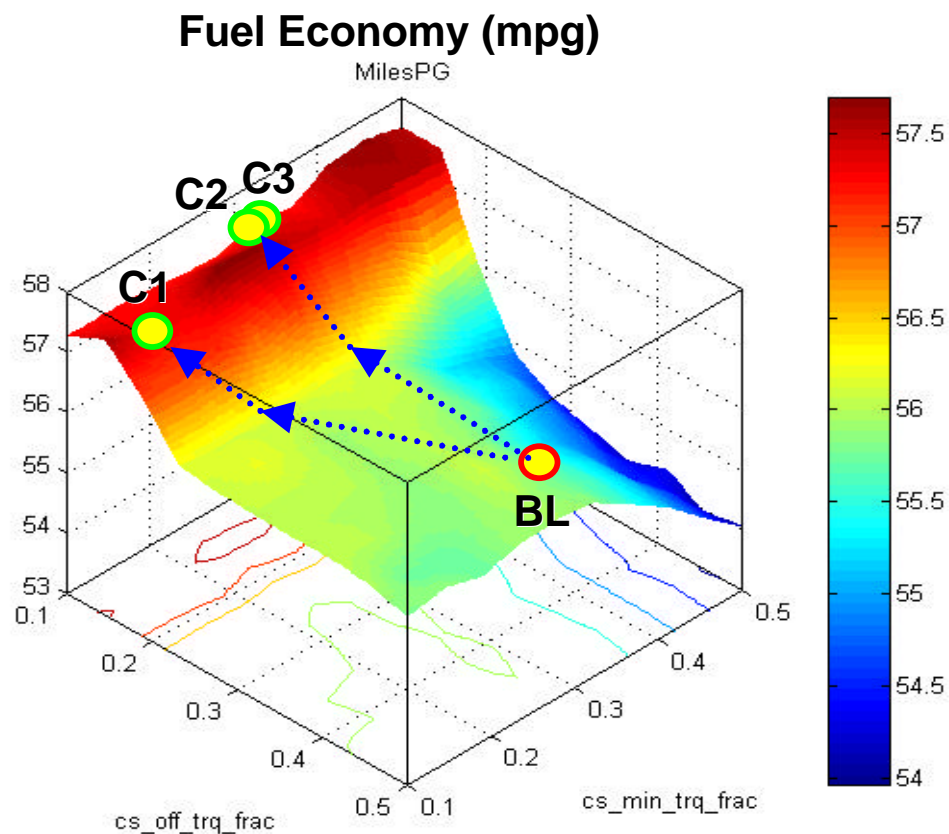
$$f = A \left(\frac{80 \text{ mpg}}{\text{fuel economy}} \right) + B \left(\frac{HC}{0.125} \right) + C \left(\frac{CO}{1.7} \right) + D \left(\frac{NOx}{0.2} \right) + E \left(\frac{PM}{0.08} \right)$$

Control Strategy Optimization: 0.5 Parallel HEV



Moving from Baseline to Optimal Fuel Economy: Minimum-Torque and Off-Torque Fractions

(FE shown for FTP only, not FTP/hwy, Parametric Sweeps Performed Starting at Baseline)



Parametric Results

Variable

MilesPG

3D Plots

Rotate

☐ Plot Slice - 3 Variables Only

X Value

Y Value

Z Value

0

Warnings/Messages

Zero DeltaSOC tolerance of 0

Save

Back Two

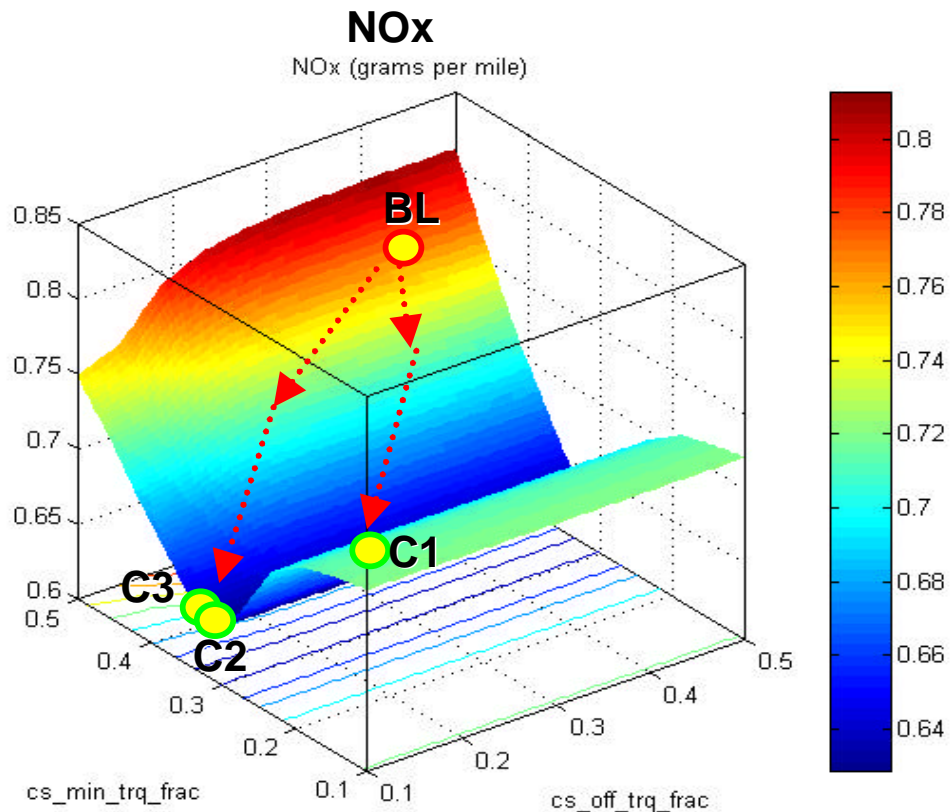
Help

Back

Exit

Moving from Baseline to Optimal Emissions: Minimum-Torque and Off-Torque Fractions

(Parametric Sweeps Performed Starting at Case 2)



Parametric Results

Variable

NOx

3D Plots

Rotate

☒ Plot Slice - 3 Variables Only

X Value

Y Value

Z Value

0

Warnings/Messages

Zero DeltaSOC tolerance of 0

Save

Back Two

Help

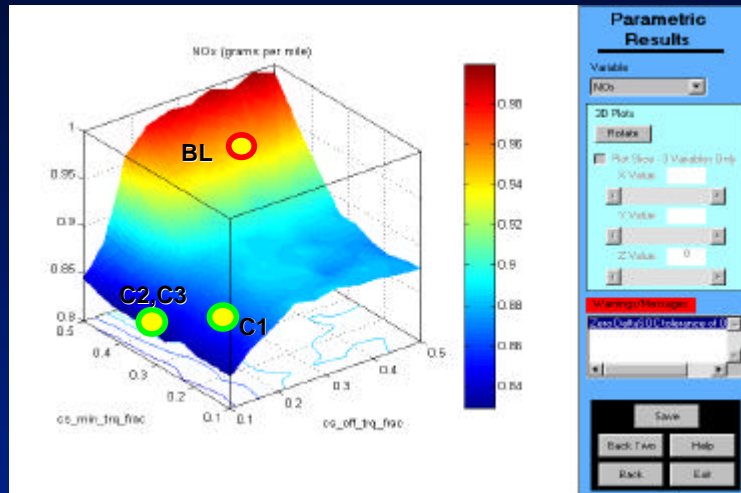
Back

Exit

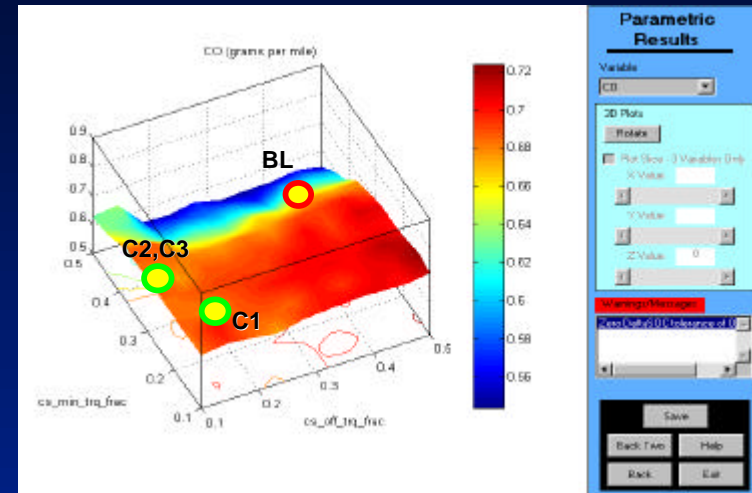
Effect of Charge-Torque and Off-Torque on Emissions

Trade-offs: Better NOx, PM, But Worse CO, HC

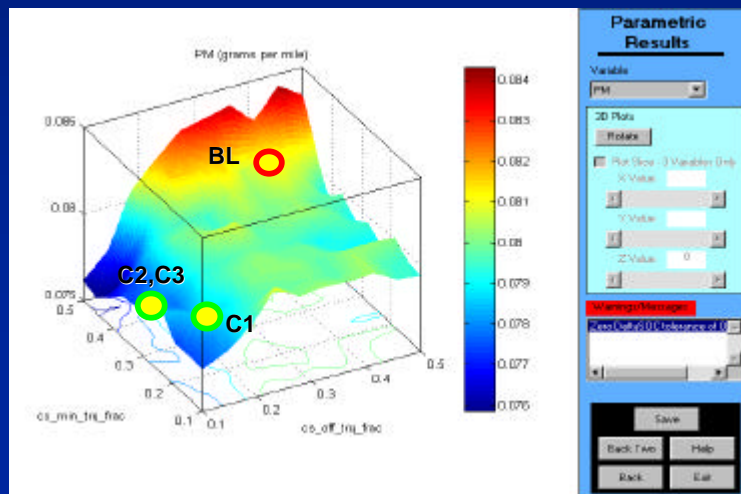
(Parametric Sweeps Performed Starting at Baseline)



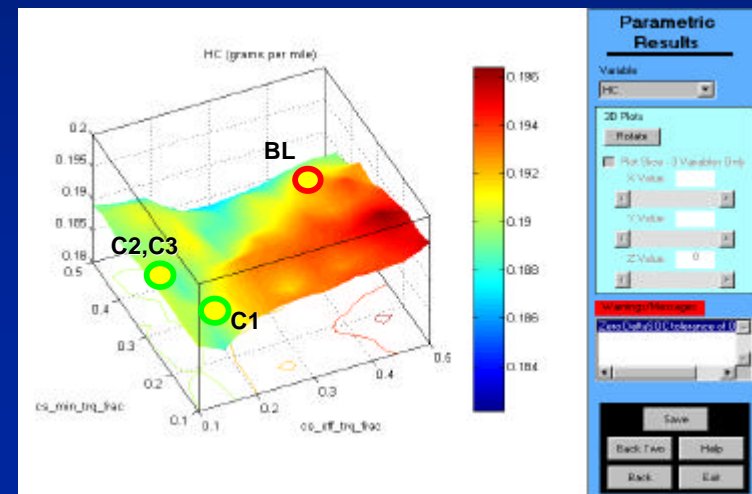
NOx



CO



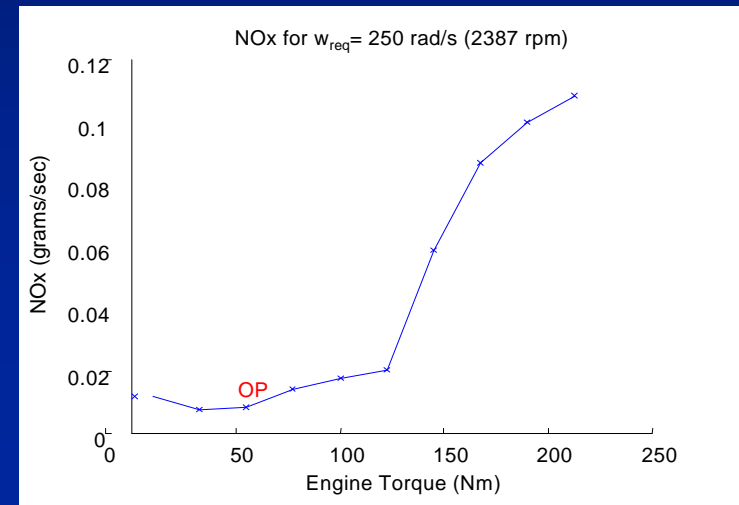
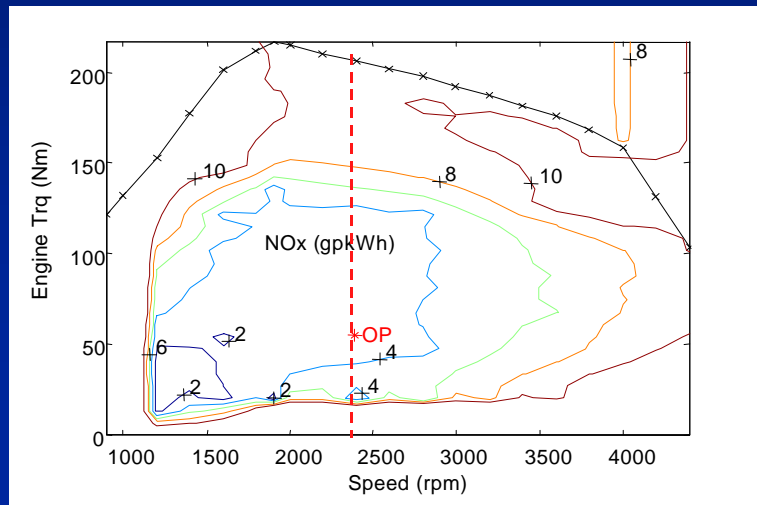
PM

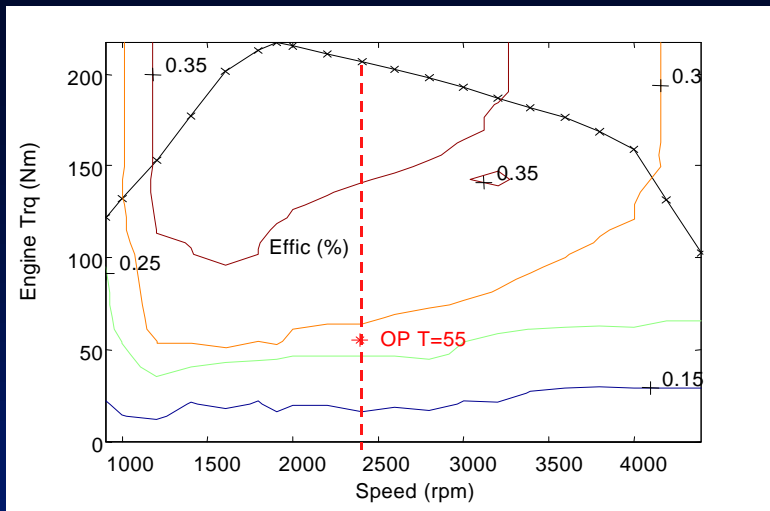


HC

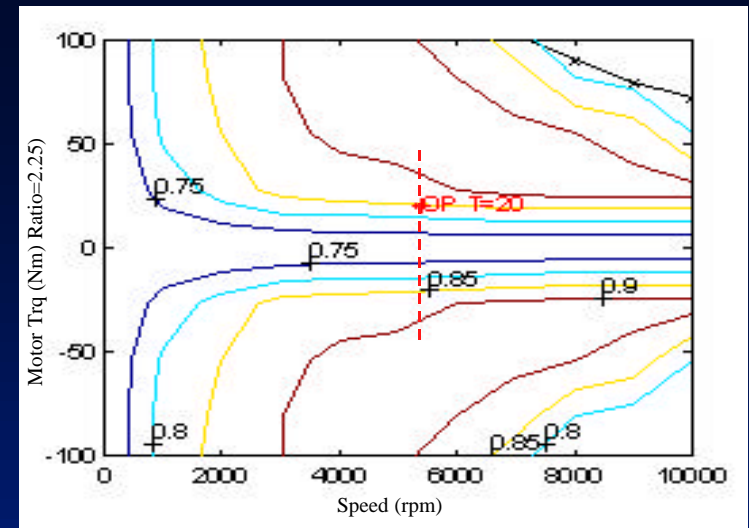
Control Strategy Development

- Goal: minimize energy usage and emissions
- User can weight importance of mpg, HC, CO, NOx, & PM
- For each operation point (a given speed), look at range of possible engine-motor torque combinations
- Performance is weighted sum of instantaneous mpg & g/mi
- Transient thermal effects (engine & catalyst) are included



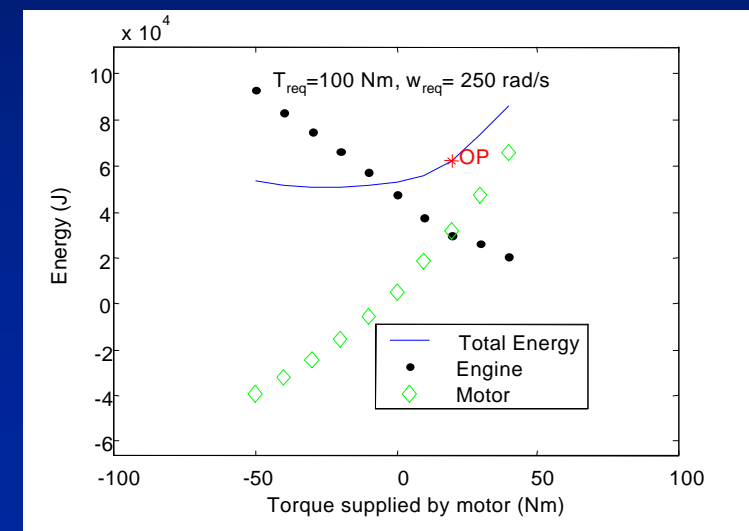


Engine Efficiency



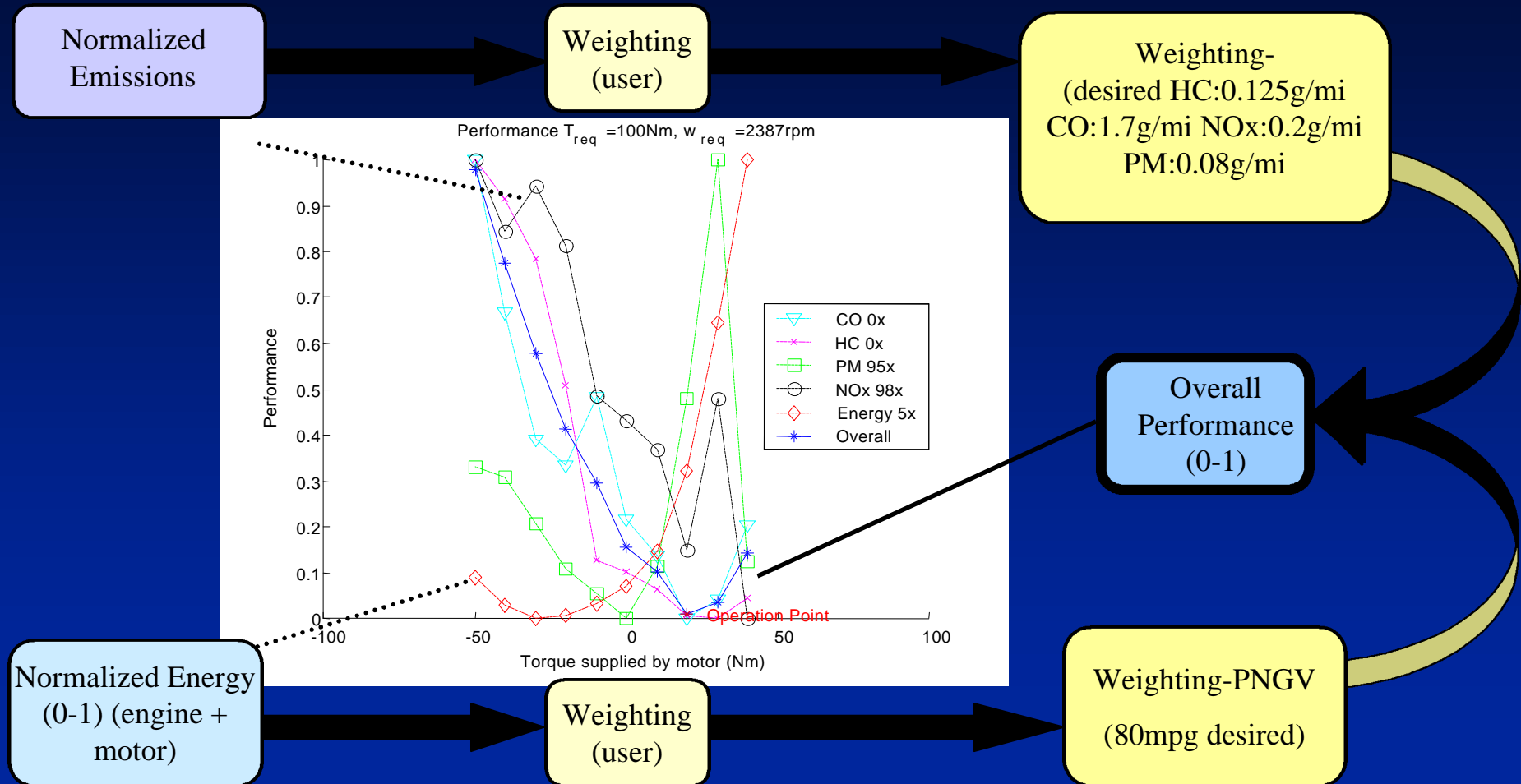
Motor Efficiency

- Energy used by engine from fuel
- Energy used by motor determined by an effective “cost” of using the motor and batteries (= energy to regain lost Δ SOC)

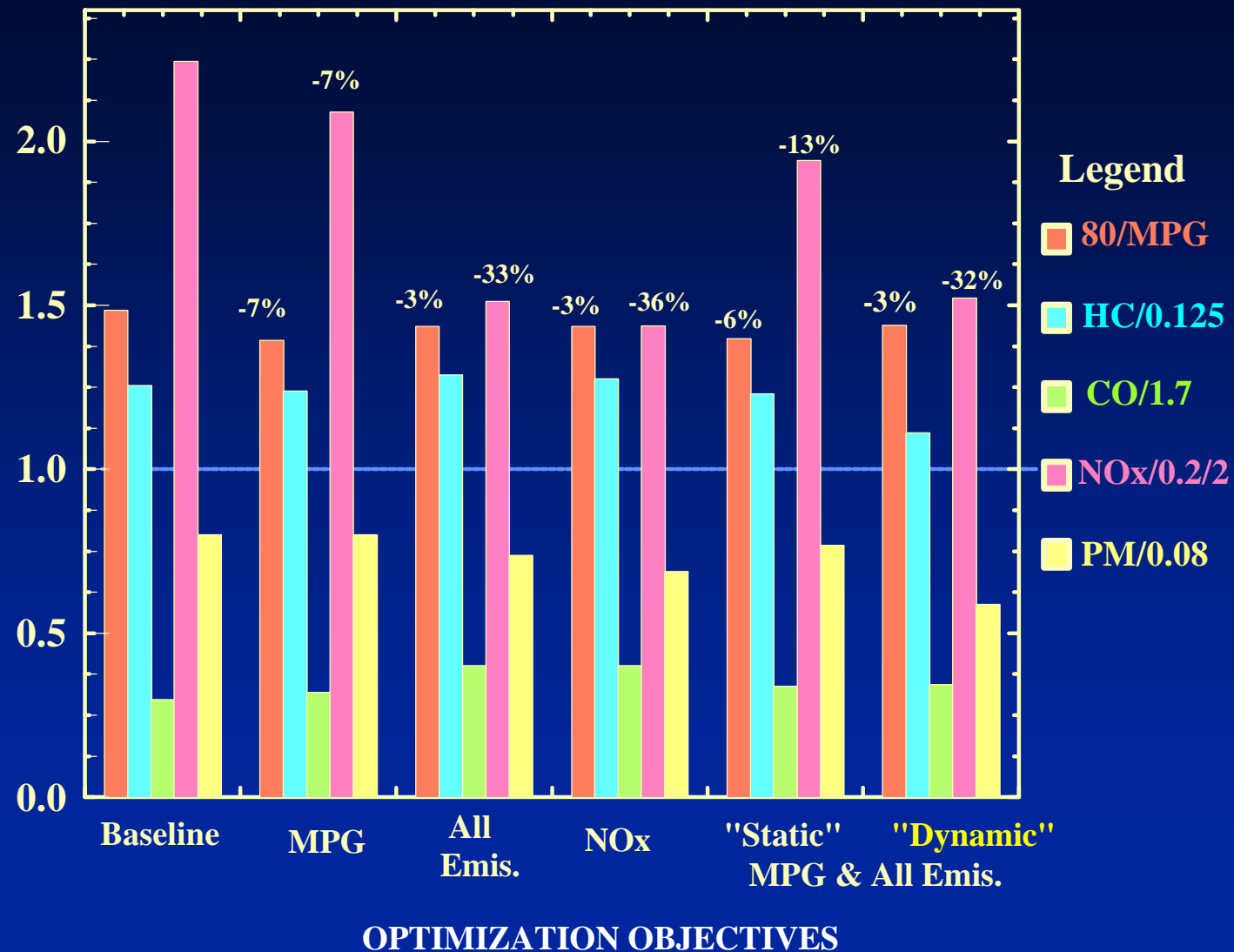


Energy Usage

Control Strategy: Performance Function



“Dynamic”Control Strategy: 0.5 Parallel HEV

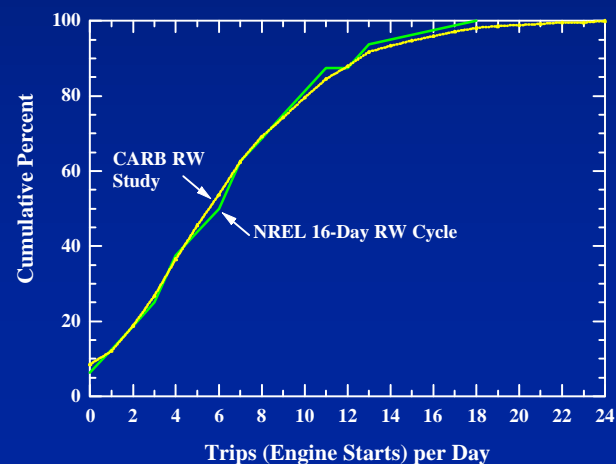
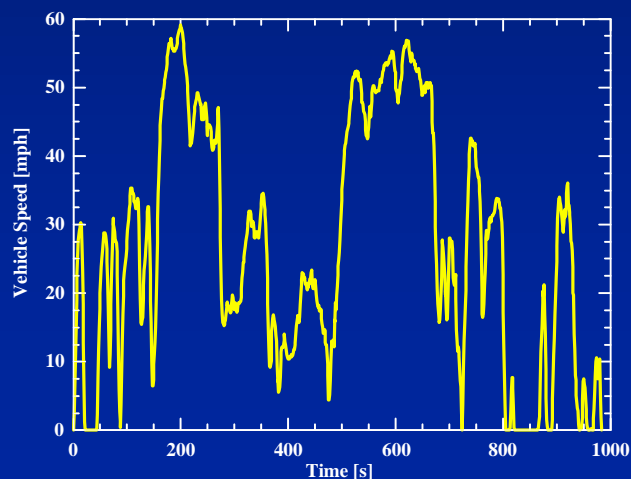
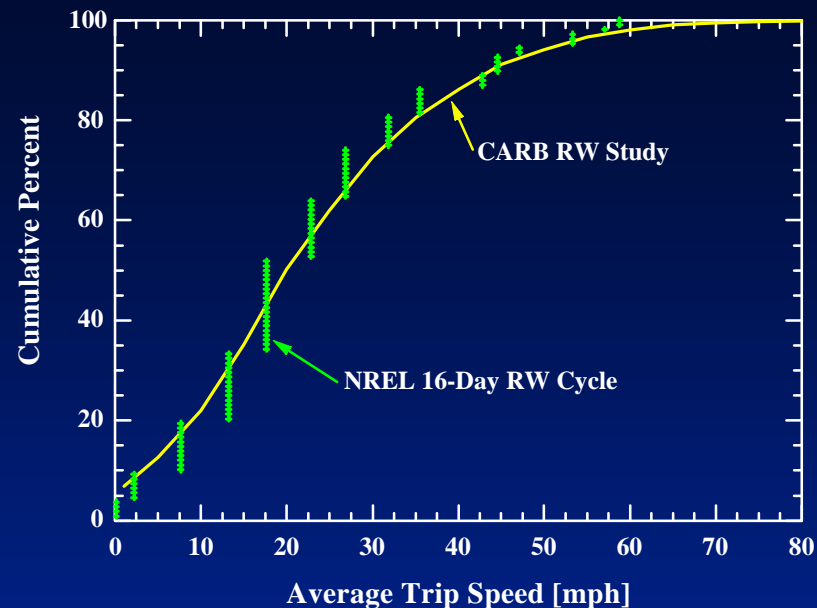


NREL 16-day "Real-World" Drive Cycle

Table 5 - Summary of CARB Unified Correction Cycles

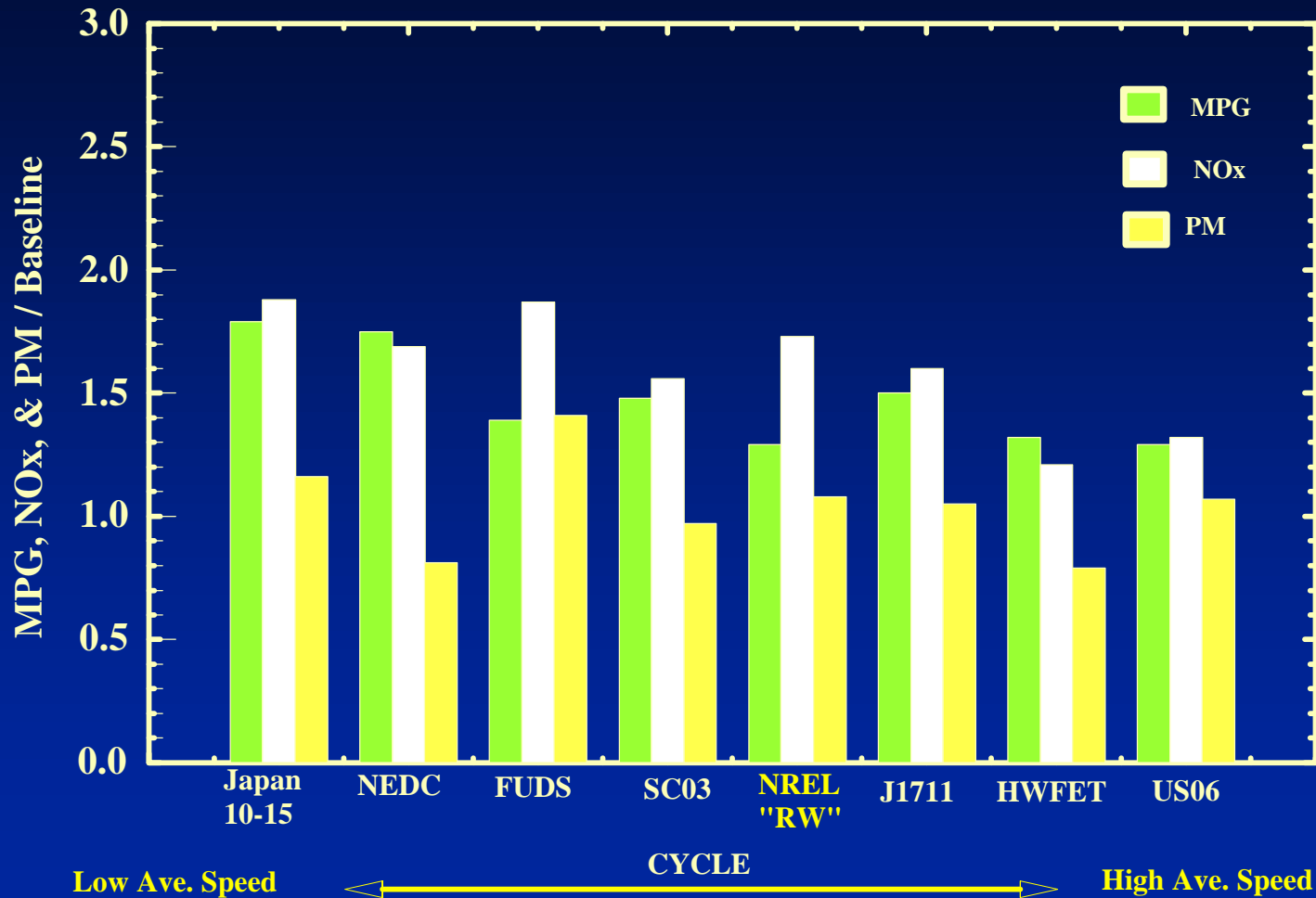
	Mean Speed (mph)	Max Speed (mph)	Max Accel (mph/s)	PKE* (ft/s ²)	Distance (miles)	Stops/ Mile	Idle (%)	Accel (%)
UCC5	2.4	12.9	2.8	1.86	0.1	31.2	60.8	18.0
UCC10	8.0	28.0	4.1	1.74	0.8	8.5	44.5	27.2
UCC15	13.3	36.5	4.6	2.20	1.5	3.84	27.7	40.5
UCC20	17.7	43.8	5.7	1.92	4.1	3.16	16.1	42.3
UCC25	22.9	49.8	5.8	1.72	5.4	2.02	13.2	43.8
UCC30	26.8	59.1	5.4	1.41	7.3	1.36	8.8	45.5
UCC35	31.9	68.7	5.6	1.27	11.9	1.00	7.9	45.7
UCC40	35.6	72.3	5.5	1.11	13.1	0.68	5.6	47.1
UCC45	44.6	71.4	5.7	1.06	16.1	0.43	3.7	45.7
UCC50	43.2	71.6	5.8	0.73	26.1	0.31	6.6	47.5
UCC55	47.4	71.1	5.6	0.66	30.3	0.23	4.7	44.8
UCC60	53.8	70.7	5.9	0.74	41.7	0.19	3.7	43.4
UCC65	57.3	81.4	5.8	0.58	61.2	0.13	3.5	44.9
UCC70	59.1	83.0	6.1	0.71	59.7	0.10	2.0	46.5
UCC75	67.65	88.7	5.9	0.67	91.1	0.07	2.0	49.9

*PKE = Positive kinetic energy



Effect of Drive Cycle on Parallel Hybrid

0.5 Hyb. Parallel



Conclusions

- Hybrid vehicles provide additional vehicle and control optimization opportunities
- For the vehicle studied, increasing the “degree” of hybridization led to higher MPG (up to 1.5X) and lower PM, but also higher NOx (up to 2X)
- Parametric sweeps of control strategy parameters provide insight about trade-offs
- Numerical optimization becomes critical when number of design variables exceeds 2 or 3

Conclusions (cont'd)

- Control strategies can be designed to balance fuel economy and emissions
 - Case 1: 7% ↑ MPG, 7% ↓ NO_x
 - Case 3: 3% ↑ MPG, 36% ↓ NO_x
 - Case 4: 6% ↑ MPG, 13% ↓ NO_x
- The drive cycle affects the relative merit of design selections: parallel HEVs show higher MPG but also higher NO_x (w.r.t. conventional) on slower cycles